



Faculty of Mechanical Engineering

**INVESTIGATION OF OSCILLATORY FLOW INSIDE
THERMOACOUSTIC SYSTEM WITH TWO DIFFERENT FLOW
FREQUENCIES**

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Master of Mechanical Engineering (Energy Engineering)

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FREQUENCIES**

WALEED ALMUKHTAR ALLAFI ALLAFI

**A thesis submitted
in fulfilment of the requirements for the degree of Master of Mechanical Engineering
(Energy Engineering)**

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2020

DECLARATION

I declare that this project entitled “Investigation of Oscillatory Flow inside Thermoacoustic System with Two Different Flow Frequencies” is the results of my own research except as cited in the references. The project has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

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APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Master of Mechanical Engineering (Energy Engineering).

Signature :

Supervisor Name : Dr. Fatimah Al-Zahrah Mohd Sa'at.

Date :

DEDICATION

To my beloved mother and father and to all who supported me to achieve this work.

ABSTRACT

Thermoacoustic system is one of the alternative technologies that provides green working principles. Complex fluid flow and energy transfer interactions happen between an oscillatory flow and a solid material during the operation of thermoacoustic device. The understanding of the flow behaviour in the interior structure in oscillating environments are one of the keys to a better design and development of the system. This study represents fluid dynamics investigation of an oscillatory flow across a parallel-plates structure inside a standing wave thermoacoustic system by using a two-dimensional ANSYS FLUENT CFD (computational fluid dynamics) of SST k- ω turbulence model. The boundary conditions of CFD model, the experimental work procedure and the validation of the model with the experimental data and theoretical solution were explained in detail. Two different operating frequencies of 14.2 Hz and 23.6 Hz were investigated. The results showed that there are several significant findings that can be highlighted based on vortex shedding pattern and entrance region investigation. Instability of vortex structures at the end of the plates were observed at low amplitude for all drive ratio cases for both frequencies. Two layers (main vortex boundary layer and secondary vortex boundary layer) were detected on each surfaces of the plate in both investigated flow frequencies. A weak vortex layer was observed to appear inside the channel near to the surface of the plates at low amplitude in the first two phases of oscillatory flow starting from 0.65% drive ratio up to the maximum drive ratio of 3% for low frequency of 14.2 Hz. For high frequency of 23.6 Hz, this weak area appeared at the second and the third phases starting from 0.83% drive ratio up to the maximum drive ratio. The secondary layer for high frequency appeared stronger than that at low frequency. The results showed that the main vortex structure was always attached to the plate for both flow frequencies. At low frequency, the maximum extension of vortex is normally detected at phase $\Phi 8$. At high flow frequency, the maximum extension of vortex happens at a later phase of $\Phi 10$. For the entrance region investigation, the axial velocity profiles at low amplitude at the first phase of oscillatory flow (for both flow directions) were significantly affected by the impinging flow for both flow frequencies. Slug velocity profile shape was detected exactly at the ends of the channel for low frequency when the flow decelerates. Two regions (entrance region and exit region) were detected at the ends of the channel for both frequencies. Entrance region for 14.2 Hz frequency extends to longer distance into the channel compared to 23.6 Hz. For both frequencies the influence of the entrance region was increasing as drive ratio increases and when the amplitude increases in each drive ratio. The fluctuation of the exit region at low drive ratio for 14.2 Hz frequency was less than that for high frequency. The exit region almost disappeared as flow amplitude increases to high drive ratios. These results are expected to contribute towards better understanding of fluid dynamic behaviour that will influence performance of a real thermoacoustic system.

ABSTRAK

Sistem Thermoacoustik adalah salah satu teknologi alternatif yang berfungsi berasaskan prinsip kerja hijau. Aliran bendalir kompleks dan interaksi perpindahan tenaga berlaku antara aliran ayunan dan bahan pepejal semasa operasi peranti thermoacoustik. Pemahaman tentang kelakuan aliran dalam struktur dalaman dalam persekitaran berayun adalah salah satu kunci kepada reka bentuk dan pembangunan sistem yang lebih baik. Kajian ini melibatkan kajian aliran ayunan merentasi struktur plat selari di dalam system termoakustik dengan gelombang berdiri menggunakan ANSYS FLUENT CFD dua dimensi (dinamik bendalir pengkomputeran) model pergolakan SST k- ω . Kondisi sempadan model CFD, prosedur kerja eksperimen dan pengesahan model dengan data eksperimen dan penyelesaian teori dijelaskan secara terperinci. Dua frekuensi operasi iaitu 14.2 Hz dan 23.6 Hz dikaji. Keputusan menunjukkan bahawa terdapat beberapa penemuan penting yang boleh diserlahkan berdasarkan corak tumpahan vorteks dan kajian kawasan masukan. Terdapat ketidakstabilan struktur vorteks di hujung plat yang diperhatikan pada amplitud rendah untuk semua kes nisbah pemacu untuk kedua-dua frekuensi aliran. Dua lapisan (lapisan sempadan vorteks utama dan lapisan sempadan vorteks sekunder) dikesan pada setiap permukaan plat dalam kedua-dua frekuensi aliran. Lapisan vorteks yang lemah diperhatikan muncul di dalam saluran berhampiran permukaan plat dengan amplitud rendah dalam dua fasa pertama aliran ayunan bermula dari nisbah pemacu 0.65% sehingga nisbah pemacu maksimum 3% untuk frekuensi rendah 14.2 Hz. Untuk frekuensi tinggi 23.6 Hz kawasan lemah ini muncul pada fasa kedua dan ketiga bermula dari nisbah pemacu 0.83% hingga nisbah pemacu maksimum. Lapisan sekunder untuk frekuensi tinggi kelihatan lebih kuat berbanding pada frekuensi rendah. Keputusan kajian menunjukkan bahawa struktur vorteks utama sentiasa melekat pada plat untuk kedua-dua frekuensi aliran. Pada frekuensi rendah, lanjutan maksimum vorteks biasanya dikesan pada fasa $\Phi 8$. Pada frekuensi tinggi, lanjutan maksimum vorteks didapati berlaku pada fasa yang lebih lambat iaitu $\Phi 10$. Untuk penyiasatan kawasan pintu masuk, gangguan aliran yang ketara berlaku kepada profil halaju pada amplitud rendah pada fasa pertama aliran ayunan (untuk kedua-dua arah aliran) pada kedua-dua frekuensi. Profil halaju berbentuk slug dikesan berlaku pada hujung saluran untuk frekuensi rendah apabila amplitud aliran menurun. Dua definisi kawasan (kawasan masuk dan kawasan keluar) dikesan berlaku pada hujung saluran untuk kedua-dua frekuensi. Rantau masuk untuk frekuensi 14.2 Hz didapati lebih besar berbanding 23.6 Hz. Bagi kedua-dua frekuensi, pengaruh kawasan masuk semakin meningkat apabila nisbah pemacu meningkat dan apabila peningkatan amplitud berlaku dalam setiap nisbah pemacu. Ketidakstabilan aliran di dalam rantau keluar pada nisbah pemacu rendah untuk kekerapan 14.2 Hz adalah kurang berbanding untuk frekuensi tinggi. Rantau keluar hampir hilang apabila amplitud untuk nisbah pemacu yang tinggi meningkat. Hasil kajian ini diharapkan dapat menyumbang pemahaman yang lebih baik mengenai tingkah laku dinamik bendalir yang akan mempengaruhi prestasi sistem thermoacoustik sebenar.

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LIST OF SYMBOLS

g	-	Gravity = 9.81 m/s
λ		Wavelength
a and c		Speed of sound
f		Oscillation frequency
ξ		Displacement
u_a and U		Velocity amplitude
ω		Angular frequency
δ_k		Thermal penetration
δ_v		Viscous penetration
ρ		Density
ρ_m		Mean density
μ		Dynamic viscosity
ν		Kinematic viscosity
K		Thermal conductivity
κ		Diffusivity of the gas
C_p		Heat capacity (specific heat) at constant pressure
y		Space between the plates
y_0		Half plate spacing

k	Wavenumbers
p_a	Ambient pressure
X	Distance from the pressure antinode
r_h	Hydraulic radius
$^{\circ}\text{C}$	Degree Celsius
Φ	Porosity
T	Temperature
Pl	Pressure amplitude
X_1 and X_2	Location of inlet and outlet of domain from antinode pressure, respectively
θ	Time phase
t	Time
ℓ	Turbulent length
D	Distance between the plates
TI	Turbulent intensity
Re	Reynolds number
T	Time step size
Dr	Drive ratio
V	Voltage

CHAPTER 1

INTRODUCTION

1.1 Background of study

The thermoacoustic devices are one of the important energy conversion systems that are providing green alternative technology which is friendly to environment. Over the most recent two decades, the over use of power sources has transformed into a vital stress for the world essentialness system to get the target of achievable improvement and focusing on lessening of global warming. One of green innovation known as thermoacoustic technology can assume a critical job in this setting in view of its preferences over traditional advancements. Thermoacoustic devices are sound-heat vitality change gadgets which work with no moving parts, utilize no-contaminating working gases, can be controlled by available sources of energy such as waste heat, solar power, and so forth. The technology can also be united with simple or/and dependable development to lower the manufacturing costs. Thermoacoustic is a part of acoustics and thermodynamics field of knowledges which concentrates on movement of heat by sound waves. The acoustics part of knowledge manages the investigation of the impact of sound exchange, like pressure changes and motion oscillations, while thermodynamic part is related to the temperature with oscillations (Swift , 1988).

Thermoacoustic devices show considerable promise when compared to conventional energy conversion technologies, for many reasons. They can be made from common materials that are available in commercial quantities according to their design simplicity. This leads to

reduction of the initial cost of such systems and makes them more suitable for use in rural areas remote from electric grids. Another critical advantage of these systems is that they work with almost no moving mechanical parts. This reduces the cost of maintenance to trivial levels and substantially increasing their operational life when compared with conventional devices, where maintenance cost is high because they require regular lubrication and replacement of worn mechanical parts. The only moving parts are the electromagnetic transducers that are used to excite the acoustic power in thermoacoustic refrigerators or to extract it in the case of thermoacoustic engines. However, this does not create any problem or necessity for maintenance process, as they are well designed for an infinite fatigue life without the need for lubrication. The working medium in these devices can be air, nitrogen, a noble gas or a mixture of these, which means that the risk of harming the environment is negligible in case of accidental leakage of working gas. Thermoacoustic devices can utilize energy supplied from any source as input energy. This can be renewable source such as solar energy or the heat of combustion contained in the exhaust of a gas turbine or other power plant. So far, thermoacoustic devices offer only up to two-third of the efficiency of conventional devices. However, research continues to enhance their efficiency.

One of the common examples of thermoacoustic phenomenon that is occurring naturally is the thunder. Lights can be named plasma discharge without wading extensively on the specificities of their production or delivery (Farouk & Antao, 2012). The rapid increase in pressure allows the acoustic and vibration wave to travel at high velocity and it appears the pressure acoustic wave as thunder. Therefore, thermoacoustic can be described as converting temperature changes to pressure (acoustic wave). The inverse is true as well, with changes in pressure leads to changes in temperature.

Other than in thermoacoustic application, oscillatory flow is also used as a technique for blending materials utilizing the mix of sharp edge and an occasionally reversing flow in a tube or a channel. This leads to potential applications in a few fields. In this situation, it is the oscillatory flow which controls the blending and this is constrained by fluctuating the frequency and amplitude of the oscillation. Hence, it is fair to state that oscillatory flow is a flow conditions that can be found in many applications (i.e. thermoacoustic energy system, ocean wave, blood flow).

This study will be focusing only on the fluid dynamics part of oscillatory flow. Two different frequencies on the oscillatory flow will be tested. The changing in the frequency is expected to effect in some other parameters or elements in the system as will be discussed in the next chapters.

1.2 Problem statement

Thermoacoustic systems are known as an innovation that offers greener options for waste heat recovery, solar power or earth amicable cooling advances. One of the problems to be discussed is the lack of knowledge of the physics of fluid dynamics and motion inside the device. This is important information to better understand the impact of flow conditions on system performance. At present, the fluid dynamic understanding within the system is based on a not clearly defined formula that is not exactly meant for thermoacoustic working environment. To establish a more exact fluid dynamics behavior of flow inside thermoacoustic systems, studies in such a direction are necessary to capture the phenomena of oscillatory flow in thermoacoustics.

1.3 Objectives of study

The objectives of this study are as follows:

1. To model the oscillatory flow across parallel-plates structure for thermoacoustic standing-wave system using ANSYS CFD.
2. To validate the model using available experimental data or published work.
3. To analyze fluid flow behavior across the stack (i.e. entrance region, velocity profile, vorticity contour).

1.4 Scope of study

The scopes for this project are:

1. To focus only on fluid dynamics aspects.
2. Two-dimensional computational fluid dynamics (CFD) model was solved in ANSYS FLUENT and the model was validated by using the available experimental data and/or theoretical calculations.
3. To do simulation and numerical analysis of standing wave thermoacoustics only.